Agricultural Systems 173 (2019) 218–232

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Mathematical programming model (MMP) for optimization of regional cropping patterns decisions: A case study

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ARTICLE INFO

Keywords:
Regional cropping pattern
Multi-objective structural planning
Robust optimization
Iran

ABSTRACT

The economic, technical and strategic factors are the three most important factors in examining the cropping patterns in Iran. Iran is geographically located in a part of the planet with specific climate constraints. Drought is one of the constraints that has been a major challenge to agricultural development for many years and has always been the subject of discussions and investigations. On the other hand, constraints such as agricultural soils, economic factors, climate change, agricultural workforce, etc., multiply the production challenges in the country. Despite such constraints, planning a coherent and targeted program for the cultivation of crops and overcome the existing problems is inevitable. The present study introduced a model for optimization of regional cropping pattern decisions, which is one of the subsets of the Multi-Objective Structural Planning (MOSP) approach, and addressed different objectives, such as economic, social and environmental objectives, separately and jointly. However, it is important to address the exchange of crops in different areas in order to achieve the fundamental objectives of determining the optimal cropping pattern. Therefore, in the proposed model of optimal regional cropping pattern, issues such as the transportation of crops and, consequently, virtual water and energy exchanges were also considered. In order to evaluate the proposed model, agricultural arable lands located in the political-geographic divisions of 23 counties of Isfahan province (Iran) were selected for examination. The results showed that in the main groups of grains and forage, a significant reduction was observed in the optimal crop area of the multi-objective model by 26% and 5%, respectively. Increasing the crop area of horticultural products by 10% in the optimal pattern of multi-objective model was another important factor in the analysis of the results. In general, in order to achieve the economic, social and environmental objectives mentioned in this study within the framework of a multi-objective planning, a 16% reduction in the level of the crop area in Isfahan province is inevitable. The results of this measure are reduction in the irrigation water consumption by 17%, increase in the profit by 58% and increase in the production by 11%. Regarding the fact that in the structural planning of cropping pattern, different and sometimes conflicting objectives are considered and the compromise between the objectives is possible in the multi-objective structural planning model, the decision makers are recommended to use this model.

1. Introduction

Agriculture, in the sense of the ways and means of utilizing water and soil resources and energy, etc. in order to meet the needs of food and clothing of human beings has always been and is the basis of many economic, social, political and cultural developments throughout history (Chatterjee et al., 2016). Considering the vast territory of Iran and the climatic diversity of different regions of country (Mosleh et al., 2017), it is imperative to achieve a suitable cropping pattern that can maximize exploitation from the production factors and production inputs, especially the limiting factor of water (Sabouhi and Mardani, 2013). Even though measures have been taken at any given time in proportion to the information available, but they have not been thorough and comprehensive (Emamzadeh et al., 2016). In sum, it seems

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https://doi.org/10.1016/j.agsy.2019.02.006
Received 20 June 2018; Received in revised form 18 December 2018; Accepted 8 February 2019
Available online 14 March 2019
0308-521X/

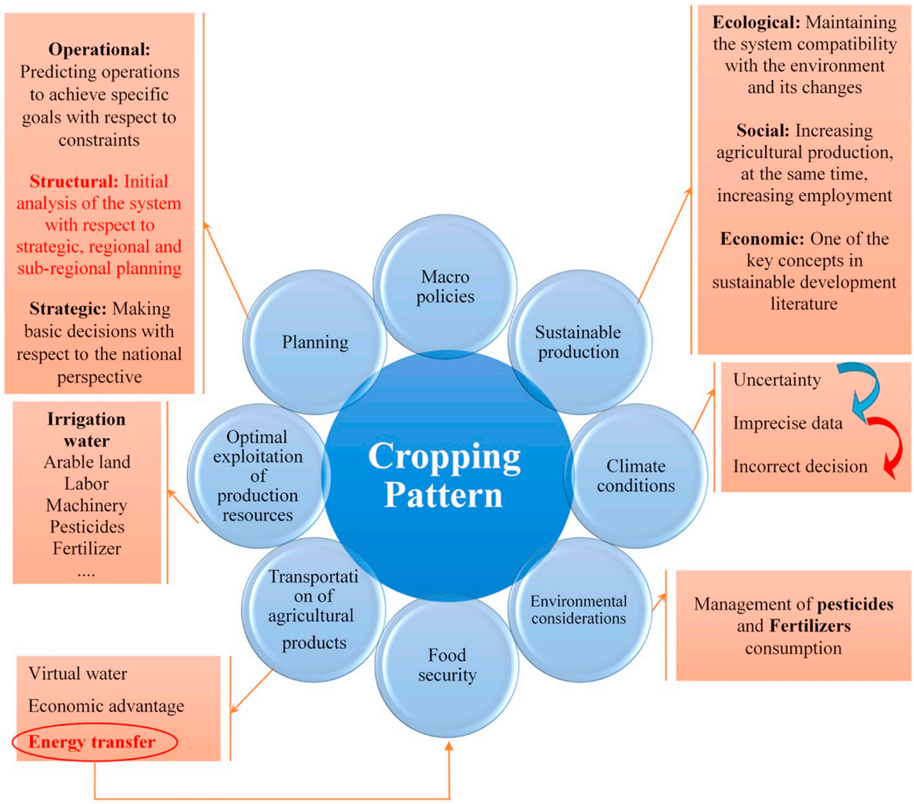

Fig. 1. The conceptual framework of cropping pattern.

that the current Iranian cropping pattern is influenced by past practices and mainly based on existing water and soil resources, and some of the economic advantages (Nikouei and Ward, 2013). Considering the changing climate and economic uncompetitive conditions, there are challenges in producing some products which must be resolved through changing the annual cropping pattern (Manos et al., 2010).

Different definitions of cropping pattern have been presented in different sources, which sometimes cover some of the objectives of the cropping pattern (Zeng et al., 2010). Considering these definitions and also using the views of some experts in Iran, the cropping pattern determines the system of cultivation based on climatic conditions (Huang et al., 2012; Wineman and Crawford, 2017), optimal utilization of resources and factors of production in line with regional potentials and economic advantages (Biswas and Pal, 2005; Manos et al., 2010), while observing the principles of sustainable agricultural production and environmental considerations (De Koeijer et al., 2003; Manos et al., 2010) in line with the country's macro policies and food security (Galán-Martín et al., 2015; Lundberg et al., 2015).

In the above definition, referring to regional potentials in using production factors provides an attitude different from determining the cropping pattern and the way of connection between different regions to produce agricultural products (Pennington et al., 2017). The importance and necessity of regional planning for planting can be attributed to the necessity of optimal use of regional production capacounties and the provision of solutions to supply and demand balances in decision making and allocation of agricultural production resources. Therefore, increasing or decreasing the crop area of various agricultural products in different regions should be taken into account due to the limited resources as well as the fertile agricultural lands, and this necessitates the design of a comprehensive model of agricultural optimal cropping pattern.

In the scientific literature of optimization, the type of appropriate decision making model in such a situation is classified into multi-criteria, multi-objective, competing objective, and multi-attribute approaches (Triantaphyllou, 2000). The common point of all these methods is that a complete agreement on a specific objective is not easily achieved. For this reason, the use of mathematical programming approach in providing optimal cropping pattern has considerable advantages and that is why it has been used in various studies (Francisco and Mubarik, 2006). In order to achieve the objective of increasing productivity by maximizing gross margins, minimizing irrigation water consumption, minimizing risk, and considering the importance of environmental attitudes toward water use, fertilizers and chemical pesticides, the consumption pattern of these inputs was optimized using the single-objective or multi-objective programming patterns.

Providing a comprehensive model that addresses all of the above is important for decision makers involved in this work at various levels of management and it follows the following objectives:

- Conducting a scheduled and structured regional planning
- Conserving the basic and renewable resources (environmental objectives)
- Reducing the production costs and making agricultural products more economic (economic objectives)
- Increasing the productivity of production factors
- Integrating the production in order to meet the needs of the country (implementation of macro national policies)
- Achieving sustainability of production in three economic, social and ecological dimensions
- Generating productive employment (social objectives)
- Managing services and inputs properly and providing integrated support to manufacturers
- Producing healthy food and maintaining health by standardizing production (food security)

In order to achieve the above objectives, it was tried in this study to model the cropping pattern of agricultural products with regard to the regional planning characteristics. Achieving the main objectives of the

Table 1
List of symbols used in the model to define the sets and variables.

Type	Symbol	Description
Sets	$d2 \in \{1, 2, \dots, D2\}$	The second level of political divisions (county)
	$j \in \{1, 2, \dots, J1\}$	The crops
	$k \in \{1, 2, \dots, K\}$	Production inputs
	$m \in \{1, 2, \dots, 12\}$	Months of the year
	$r \in \{1, 2, \dots, R\}$	Industrial units and processing industries
	$q \in \{1, 2, \dots, Q\}$	Animal husbandry and poultry breeding units
Variables	$Land\_V_j^{d2}$	The amount of land allocated to the crop j in the d2 county
	$Water\_V_{jm}{}^{d2}$	The amount of water allocated to the crop j in the d2 county
	$NetBenefit\_V^{d2}$	Total gross profit in d2 county
	$Prod\_d2\_V_j^{d2}$	The amount of production from the crop j in the d2 county
	$Obj\Pr ofit\_V$	Total gross margin (The objective function variable)
	$ObjWater\_V$	Total Irrigation Water (The objective function variable)
	$ObjPes\,\&\,Fert\_V$	Total cost of fertilizers and pesticides (The objective function variable)
	$ObjLabor\_V$	Total number of labor (The objective function variable)
	$ObjEnergy\_V$	The total amount of energy generated due to consuming crops (the objective function variable)
	$CityTrans\_V_j^{d2,\ d2}$	The amount of transport of crops from d2 county to other counties
	$EXP\Pr ovince\_V_j^{d2}$	The export volume of crop j from d2 county to the outside of the province
	$IMP\Pr ovince\_V_j^{d2}$	The import volume of crop j to the d2 county from the outside the province
	$IMPVirWater\_V_j^{d2}$	The volume of virtual water imports from crop j in the d2 county
	$EXPVirWater\_V_j^{d2}$	The volume of virtual water exports from crop j in the d2 county
	$NetIMPVirWater\_V_j^{d2}$	Net import volume of virtual water from crop j in the d2 county
	$TotalEnergy\Pr od\_V_j^{d2}$	Total energy generated from the crop j in the d2 county
	$NetEnergyIMP\_V_j^{d2}$	Net energy import for crop j in the d2 county
	$Energy\operatorname{Re} q\_Min\_V^{d2}$	Minimum energy required by residents in the d2 county

cropping pattern, according to the definition in the preceding section, requires attention to different and sometimes contradictory objectives such as maximizing gross profit (economic objective), minimizing the cost of using fertilizers and pesticides (environmental objective), minimizing consumption of irrigation water (environmental objective) and maximizing the use of labor (social objective). Therefore, the proposed model in this study is in the form of a multi-objective programming model.

2. Materials and methods

2.1. Conceptual framework of cropping pattern

Fig. 1 clearly illustrates the general understanding of the concept of cropping pattern and the fundamental concepts involved in this topic. With a systematic look at this picture, it is necessary to use modern and efficient planning techniques that can measure all the factors affecting agricultural sector policies and its economic effects. It is noted that in order to achieve an optimal cropping pattern, eight basic issues of planning type, optimal utilization of agricultural production resources, agricultural products transportation, food security, environmental conditions, weather conditions, production sustainability and macro policies have to be considered. In the remaining parts of this section, the most important close relationship between these components and the cropping pattern will be examined.

In terms of planning, the cropping pattern can be divided into three broad areas of strategic, structural or implementation planning. The collection of these plans is not incompatible with each other in different levels, but because of information, cost, credit, and technical limitations (a large number of variables and parameters), they complement each other (Manos et al., 2010). In this study, planning of cropping pattern has been considered at the level of political divisions (county and province), which results in the preparation of a structural planning.

Currently, the most important environmental concerns of agricultural activities are the use of inputs from the non-agricultural sector, such as fertilizers and chemical pesticides, to increase agricultural production and respond to the increasing demand generated by population growth. This situation in production systems causes a serious conflict between environmental objectives and economic objectives of farmers. The lack of attention to the existence of such conflicts in many of the cropping patterns proposed in Iran has led to the disapproval of these patterns by farmers (Emamzadeh et al., 2016).

Food security in each country is one of the important conditions for the establishment of national security in that country. Since achieving food security requires the development of agricultural products, paying attention to the agricultural structure in different societies and improvement of agricultural situation, as well as optimal allocation of production factors in order to produce more per unit area are of great importance. In this regard, it is clear that the more reliance on domestic products, the more strengthened food security, and this will contribute to the stability of national security. But too much attention to domestic production should not lead to exorbitant national costs and non-optimal allocation of production factors (Karami et al., 2012).

The use of the term “virtual water” in the agricultural application links the three concepts of water, food, and trade of these products together (Hoekstra and Hung, 2005). As a consequence of using the concept of trade in this topic, the flow of agricultural goods exchange between different regions also intensifies. The two concepts of water and food also push the mind behind the stage of the exchange of products between different regions, i.e. the production stage, leading to the emergence of a broad topic of cropping pattern (Rasul, 2014). There is also such a process in the trend of exchanging energy through the transportation of agricultural products. In addition, the topic of energy exchange is related to the food security (Zhang and Vesselinov, 2017). Food trading has a direct relationship with food security leading to the direct purchase of food in the world markets using the export earnings. Comprehensive and regional trade allows countries to buy or sell food in the global market, moderate or adjust the production in the event of economic shocks, generate revenue for the government and achieve global economic growth, each of which has a direct or indirect effect on the nutritional status of the people of the country. Therefore, whenever a country has domestic production areas for imported products, but it cannot take advantage of national capabilities and capacounties due to lack of necessary supports, the food security factor and, consequently, the national security factor will be worrying.

2.2. Mathematical programming model

The main structure of the mathematical programming model is based on recent studies on the modeling of the regional cropping

Table 2
List of symbols used in the model to define parameters.

Symbol	Description
$LandSch_{jm}{}^{d2}$	Coefficient of the land occupation for the crop j and month m in the d2 county
$InputCost_{jk}{}^{d2}$	The input cost of k for crop j in the d2 county
$LandRHS^{d2}$	Amount of arable land in the d2 county
$NetWater\,\mathrm{Re}\,q_{jm}{}^{d2}$	The amount of net water required to plant one hectare of crop j in the month m for the d2 county
$WaterEff^{d2}$	Irrigation efficiency in the d2 county
$WaterRHS_m{}^{d2}$	The amount of water available in month m for the d2 county
$InputAMT_{jk}{}^{d2}$	The amount of input of k required to plant one hectare of crop j in the d2 county
$CropYield_j{}^{d2}$	Average yield of crop j in the d2 county
$InputRHS_k{}^{d2}$	Available amounts of input k in the d2 county
$NetBenifitCurrent^{d2}$	Current benefit of the d2 county
$CostDista_j$	Coefficient of transportation cost of the crop j
POP^{d2}	The population of urban and rural areas in the d2 county
$UNITDM_j$	Per capita consumption of crop j
$RURPOP^{d2}$	The population of rural areas in the d2 county
$AnimPOP_q{}^{d2}$	The livestock and poultry population in the d2 county
$WNM_{qj}{}^{d2}$	Per capita consumption of q type of livestock and poultry for crop j in the d2 county
$PHEAD_j$	Per capita self-consumption in rural areas for crop j
$WNM_{rj}{}^{d2}$	Consumption requirement of crop j for industry r in the d2 county
$CityDista^{d2,\ d2}$	The distance between different counties in the province
$Out\,\mathrm{Pr}\,ovinDista_j$	The distance related to the exit of the product j from the province
$CropIMP\,\mathrm{Pr}\,ice_j{}^{d2}$	The import price of crop j to the d2 county
$VirtualWater_j{}^{d2}$	The volume of virtual water of crop j in the d2 county
$Calori_j$	The energy generated due to consuming the crop j in a certain amount of unit of weight
$Energy\,\mathrm{Re}\,q$	Per capita energy equipment
$Crop\,\mathrm{Pr}\,iceCo_j{}^{d2}$	Price coefficient of crop j in the d2 county
$Trans\,\mathrm{Pr}\,ice_j{}^{d2}$	Price of crop j including the transportation cost for the d2 county
$QEXP_{j1}{}^{d2}$	Export contribution of product j in the d2 county
$CropIMPCity\,\mathrm{Pr}\,ice_j{}^{Exp,\ d2}$	Price coefficient of imports between counties for the crop j
$DiffCropCity\,\mathrm{Pr}\,ice_j{}^{d2,\ IMP}$	Price difference between counties for crop j
$DiffCrop\,\mathrm{Pr}\,ice_j{}^{d2}$	Price difference of the counties in the province with the counties outside the province for the crop j

pattern and transportation of agricultural products (Mosleh et al., 2017; Pal et al., 2003; Ren et al., 2017). This model contains parts of the objective functions and its related constraints, which are subsequently reviewed.

Due to the large number of symbols used in this study, and also for better understanding, the symbols related to each of the sets and variables are explained in Table 1 and the parameters are described in Table 2. This avoids readers' confusion in the proposed model. It should be noted that at the end of the signs used for decision variables, a V letter is used to identify them better when investigating the model. The level of political divisions in Iran includes provinces (d1), counties (d2), rural (d3), and Village (d4). As already mentioned, the proposed model is a structural model and the study areas will be considered at the county level (d2).

2.2.1. Objective functions

Different objectives of the regional cropping pattern can be envisaged. Due to the flexibility of the proposed model, it is easy to think about different objectives. The algebraic form of these objectives is described in their order of importance in Eq. (1):

$$Obj\begin{cases} 1 \rightarrow Max{:}Obj\,\mathrm{Pr}\,ofit\_V = \sum_{d2=1}^{D2} NetBenefit\_V^{d2} \\ 2 \rightarrow Max{:}ObjWater\_V = \sum_{d2=1}^{D2}\sum_{j=1}^{J} NetIMPVirWater\_V_j^{d2} \\ 3 \rightarrow Min{:}ObjPse\&Fert\_V = \sum_{d2=1}^{D2}\sum_{j=1}^{J} Input\,\mathrm{Cos}\,t_{jk}^{d2} \quad \forall\ k = \{\text{pesticide, fertilizer}\} \\ 4 \rightarrow Max{:}Obj\mathrm{Labor}\_V = \sum_{d2=1}^{D2}\sum_{j=1}^{J} InputAMT_{jk}^{d2} Land\_V_j^{d2} \quad \forall\ k = \{\text{Labor}\} \\ 5 \rightarrow Min{:}ObjEnergy\_V = \sum_{j=1}^{J}\sum_{d2=1}^{D2} NetEnergyIMP\_V_j^{d2} \end{cases} \tag{1}$$

In Eq. (1), the first objective is to maximize the profit (economic), and the second is to maximize the net import of virtual water (environmental), which implicitly minimizes the use of irrigation water. The third and fourth objectives are to minimize the cost of using fertilizers and pesticides (environmental) and maximize the use of labor (social). The last objective is to minimize the net import of energy from agricultural products (food security), which implicitly maximizes the production of more caloric crops. Obviously, the measurement criteria are quite different for the mentioned objectives. As an example, the objective of maximizing profits which is measured by the monetary unit is different from the objective of minimizing irrigation water which is measured by volume. The use of multi-objective programming methods requires the use of methods to align (normalization) measurement criteria to different objectives. There were various methods to normalize the mentioned objectives, and, in any study where multi-objective programming methods were employed, one of these methods was used. One of these methods used in the present study was weight normalization using fuzzy set theory. It should be noted that this theory was not used in this study to apply the uncertainty conditions. Rather, it was only used to normalize the objectives based on the study by Jones and Barnes (2000).

2.2.2. Set of constraints

The above objectives are accomplished within a set of constraints. In this regard, the total size of land allocated to crops should not exceed the total arable land for each county (per region) and per month:

$$\sum_{j=1}^{J} LandSch_{jm}^{d2} Land\_V_j^{d2} \leq LandRHS^{d2} \qquad \forall\ d2,\ m \tag{2}$$

In Eq. (2), the coefficient of land occupation, and in other words, the number of months the land is occupied by a crop is considered. Given that the planning presented in this study is a regional planning that is a subset of structural planning, the application of the occupation coefficient is sufficient in this constraint. The study of the crop rotation is possible in operational planning and at levels with lower scales (Wang et al., 2016).

The balance of different levels of irrigation water consumption in terms of month, county and crop (Eq. (3)) is one of the most important factors in determining the cropping pattern. In this regard, attention is paid to the non-diversion of the pattern from available water (Eq. (4)) for different regions and months.

$$Water\_V_{jm}^{d2} = (NetWater\,Req_{jm}^{d2}/WaterEff^{d2})Land\_V_{j}^{d2} \quad \forall\ d2, j, m \tag{3}$$

$$\sum_{j=1}^{J} Water\_V_{jm}^{d2} \le WaterRHS_{m}^{d2} \quad \forall\ d2, m \tag{4}$$

In Eq. (3), the problem of irrigation efficiency and the conversion of net water requirement of crops to the water requirement are addressed. Eqs. (3) and (4) create an upper limit for water consumption in terms of region and month. In other words, in the accounting Eq. (3), water consumption was determined for product *j* in region *r* for month *m*, and then, it was restricted using Eq. (4).

The non-diversion of the amount of using each agricultural input from the available amount of these inputs is one the constraints (Eq. (5)) of the cropping pattern.

$$\sum_{j=1}^{J} InputAMT_{jk}^{d2} Land\_V_{j}^{d2} \le InputRHS_{k}^{d2} \quad \forall\ d2, k \tag{5}$$

Calculating the net benefit from production of agricultural products for each county in the proposed model has different components due to the ability to transfer products between regions (counties) as well as to the outside the province (Eq. (6)). The first component of this equation is related to the calculation of the net benefit from sales of crops inside the county of production. The second component is related to the cost imposed on the county which imports the crops from other counties. The third component is related to the benefit from the export of the crop from the county of production to the county demanding that crop. The fourth component is related to the benefit from the export of the crop from the county of production to the outside of the province. Finally, the fifth component is related to the cost imposed on the county that imports the crop from outside the province. The basic structure of these components is derived from Venables and Limão's (2002) study, which is based on the bid rent theory in Von Thünen's model.

$$\begin{aligned} NetBenefit\_V^{d2} = & \\ & \sum_{j1=1}^{J1}\sum_{k=1}^{K} (Crop\,PriceCo_{j}^{d2} CropYield_{j}^{d2} - InputCost_{jk}^{d2})Land\_V_{j}^{d2} \\ & - \sum_{j=1}^{J}\sum_{EXP}^{D2} CropIMPCity\,Price_{j}^{Exp,d2} CityTrans\_V_{j}^{Exp,d2} \\ & + \sum_{j=1}^{J}\sum_{IMP}^{D2} (DiffCropCity\,Price_{j}^{d2,IMP} - CityDista^{d2,IMP}CostDista_{j})CityTrans \\ & \_V_{j}^{d2,IMP} \quad \forall\ d2 \\ & + \sum_{j=1}^{J} (DiffCrop\,Price_{j}^{d2} \\ & - CostDista_{j} Out\,ProvinDista_{j})EXP\,Province\_V_{j}^{d2} \\ & - \sum_{j=1}^{J} CropIMP\,Price_{j}^{d2} IMP\,Province\_V_{j}^{d2} \end{aligned} \tag{6}$$

The existence of a constraint that is capable of preventing the loss of the current net benefit of each county seems to be necessary in the proposed model (Eq. (7)).

$$NetBenefit\_V^{d2} \ge NetBenifitCurrent^{d2} \quad \forall\ d2 \tag{7}$$

The amount of crop j existed in the d2 county after the transfer of crops is obtained through the sum of the domestic production and the domestic and foreign imports of that crop and the deduction of this amount from the domestic and foreign exports of that crop (Eq. (8)):

$$\begin{aligned} & CropYield_{j}^{d2} Land\_V_{j}^{d2} - EXP\,Province\_V_{j}^{d2} \\ & + IMP\,Province\_V_{j}^{d2} + \sum_{EXP}^{D2} CityTrans\_V_{j1}^{Exp,d2} \\ & - \sum_{IMP}^{D2} CityTrans\_V_{j1}^{d2,IMP} = Prod\_d2\_V_{j}^{d2} \quad \forall\ j, d2 \end{aligned} \tag{8}$$

Settlement of supply and demand balance of each county for each crop is subject to the restrictions required for the proposed cropping pattern (Eq. (9)). Demand for crops is determined depending on the applicant.

$$\begin{aligned} & Prod\_d2\_V_{j}^{d2} = (POP^{d2}UNITDM_{j}) + (RURPOP^{d2}PHEAD_{j}) \\ & + \left(\sum_{q=1}^{Q} AnimPOP_{q}^{d2} WNM_{qj}^{d2}\right) + \sum_{r=1}^{R} WNI_{rj}^{d2} \quad \forall\ j, d2 \end{aligned} \tag{9}$$

In Eq. (9), the four terms of the right side of the equation are related to the urban and rural areas (food security), self-consumption needs, the needs of intermediate units of livestock husbandry and poultry breeding, and the need of intermediate industrial and processing units to produce crops in each county.

There are four constraints for controlling inter-regional and trans-provincial exports and imports. These four set of constraints are designed to prevent the lack of coordination between supply and demand in different regions; so that if a county has a surplus of supply of a crop and exports this crop, it should not have any imports of this crop from other counties or from outside the province. The algebraic form of this condition is presented in four algebraic relations:

$$\sum_{EXP}^{D2} CityTrans\_V_{j1}^{Exp,d2} \sum_{IMP}^{D2} CityTrans\_V_{j1}^{d2,IMP} = 0 \quad \forall\ j, d2 \tag{10}$$

$$EXP\,Province\_V_{j}^{d2} IMP\,Province\_V_{j}^{d2} = 0 \quad \forall\ j, d2 \tag{11}$$

$$EXP\,Province\_V_{j}^{d2} \sum_{EXP}^{D2} CityTrans\_V_{j1}^{Exp,d2} = 0 \quad \forall\ j, d2 \tag{12}$$

$$IMP\,Province\_V_{j}^{d2} \sum_{IMP}^{D2} CityTrans\_V_{j1}^{d2,IMP} = 0 \quad \forall\ j, d2 \tag{13}$$

Eq. (10) controls the entry and exit of the products between counties. To better understand this equation, suppose that 10 tons of wheat is exported from county 1 to county 2. Therefore, county 1 encounters a surplus of supply, and, it should not have any imports of this product. In other words, when $CityTrans\_V_{wheat}{}^{12}$ is 10 tons, $CityTrans\_V_{wheat}{}^{21}$ should be zero. This is easily performed using Eq. (10); since the product of these two variables should be zero. Eq. (11) controls the trans-provincial entry and exit of products, and its mechanism of action is similar to Eq. (10). Eqs. (12) and (13) are related to controlling inter-county and trans-provincial exports and imports respectively, such that when a product is exported from a county to the outside of the province, this product should not be imported from other counties to the exporting county.

In order to prevent excessive exports of crops from the areas under investigation, a set of constraints was imposed on the export boundaries of these crops with the following algebraic relations:

$$EXP\Pr ovince\_V_j^{d2} + \sum_{IMP}^{D2} CityTrans\_V_{j1}^{d2,IMP} \leq QEXP_{j1}^{d2}\,CropYield_j^{d2}\,Land\_V_{j1}^{d2} \qquad \forall\, j,\, d2 \tag{14}$$

In this study, the concept of virtual water was used to do interconnected evaluations on the consumption of agricultural water. In general, the virtual water content of a crop can be calculated as a ratio of the average water requirement to the average yield of the product (Hoekstra and Hung, 2005):

$$VirtualWater_j^{d2} = \left(\sum_{m=1}^{12} (NetWater\,\mathrm{Re}\,q_{jm}^{d2})/WaterEff^{d2}\right)/CropYield_j^{d2} \tag{15}$$

The virtual water exchange for each crop which involves the import and export of that crop is calculated through multiplication of the import or export quantity of that crop by the amount of its virtual water consumption:

$$IMPVirWater\_V_j^{d2} = VirtualWater_j^{d2*}(IMP\Pr ovince\_V_j^{d2} + CityTrans\_V_{j1}^{Exp,d2}) \tag{16}$$

$$EXPVirWater\_V_j^{d2} = VirtualWater_j^{d2*}(EXP\Pr ovince\_V_j^{d2} + CityTrans\_V_{j1}^{d2,IMP}) \tag{17}$$

In Eqs. (16) and (17), virtual water import and export for product j in county d2 is calculated respectively. What is important in these equations is that to calculate virtual water, the product of virtual water (15) should be calculated in the total inter-provincial and trans-provincial export (import).

The net import of virtual water can be written as follows:

$$NetIMPVirWater\_V_j^{d2} = IMPVirWater\_V_j^{d2} - EXPVirWater\_V_j^{d2} \tag{18}$$

The amount of energy consumed by crops should provide at least the amount of energy needed by each region for its inhabitants (Eq. (21)). In order to apply this constraint, the minimum amount of energy required by each county must be first calculated, which is carried out through the multiplication of the number of inhabitants in each county by the amount of energy needed per person (Eq. (19)). Subsequently, the total amount of energy from crops consumption is calculated to be the equivalent of the energy generated inside the region minus amount of net imports of energy from the consumption of crops (Eq. (20)).

$$Energy\,\mathrm{Re}\,q\_Min\_V^{d2} = POP^{d2}Energy\,\mathrm{Re}\,q \qquad \forall\, d2 \tag{19}$$

$$TotalEnergy\Pr od\_V_j^{d2} = Calori_j\,CropYield_j^{d2}\,Land\_V_j^{d2} - NetEnergyIMP\_V_j^{d2} \qquad \forall\, d2, j \tag{20}$$

$$\sum_{j=1}^{J} TotalEnergy\Pr od\_V_j^{d2} \geq Energy\,\mathrm{Re}\,q\_Min\_V^{d2} \qquad \forall\, d2 \tag{21}$$

The amount of net imports of energy from agricultural products consumption is calculated using Eq. (22), through subtraction of energy imports (Eq. (23)) from energy exports (Eq. (24)).

$$NetEnergyIMP\_V_j^{d2} = IMPEnergy\_V_j^{d2} - EXPEnergy\_V_j^{d2} \tag{22}$$

$$EXPEnergy\_V_j^{d2} = \left(EXP\Pr ovince\_V_j^{d2} + \sum_{IMP}^{D2} CityTrans\_V_j^{d2,IMP}\right)Calori_j \qquad \forall\, j,\, d2 \tag{23}$$

$$IMPEnergy\_V_j^{d2} = \left(IMP\Pr ovince\_V_j^{d2} + \sum_{EXP}^{D2} CityTrans\_V_j^{Exp,d2}\right)Calori_j \qquad \forall\, j,\, d2 \tag{24}$$

2.2.3. Uncertain data and robust optimization

One of the classic assumptions in mathematical programming in a condition of certainty is that all parameters (input data) are fully known and definite. In the present study, the robust optimization model was used to apply uncertain conditions. An uncertain parameter could be converted into randomized disturbances (Ben-Tal and Nemirovski, 2000).

$$\tilde{a}_{ij} = \bar{a}_{ij} + \tilde{\eta}_{ij}\varepsilon\bar{a}_{ij} = \bar{a}_{ij} + \tilde{\eta}_{ij}\hat{a}_{ij}. \tag{25}$$

Where, $\bar{a}_{ij}$ is the nominal value of the uncertain parameter, and determines a certain level of uncertainty. $\tilde{\eta}_{ij}$ are random variables distributed symmetrically in the $[-1,1]$ range. $\hat{a}_{ij}$ is obtained by multiplying the nominal value of variable ($\bar{a}_{ij}$) and a certain level of uncertainty (ε). Therefore, parameter has a symmetric and bounded distribution in $[\bar{a}_{ij} - \hat{a}_{ij}, \bar{a}_{ij} + \hat{a}_{ij}]$, which is used in the following optimization problem (Eq. (26)).

$$\begin{aligned} &Maximize \quad cx \\ &subject \quad to \quad \sum_{j=1}^{n} \tilde{a}_{ij}x_j \leq b, \qquad \forall\, i, j \in J_i \\ &l \leq X \leq u. \end{aligned} \tag{26}$$

Where, J_i is a subset of indices related to the uncertain parameter $\tilde{a}_{ij}$ determined for each i constraint. To control conservatism, Γ_i parameter is introduced to which the natural number in the $[0,J_i]$ range could be attributed. Therefore, by introducing B_i variable which is a function of primary variables (x) and the conservatism parameter (Γ_i), the principle formulation of robust optimization is written as Eq. (27).

$$\begin{aligned} &Maximize \quad cx \\ &subject\ to \quad \bar{a}_{ij}x + B_i(x,\Gamma_i) \leq b_i \quad \forall\, i \\ &\qquad x \geq 0 \end{aligned} \tag{27}$$

According to the study conducted by Bertsimas and Sim (2004), for maximum preservation of the model against uncertain data, the equality 28 is necessary.

Ac

$$B_i(x,\Gamma_i) = \max_{\{S_i \cup \{t_i\} | S_i \subseteq J_i, |S_i| = [\Gamma_i], t_i \in J_i \setminus S_i\}} \left\{\sum_{j \in S_i} \hat{a}_{ij}x_j + (\Gamma_i - [\Gamma_i])\hat{a}_{it_i}x_t\right\} \tag{28}$$

By placing Eq. (28) in the formulation of robust optimization (Eq. (27)), a robust nonlinear optimization is produced. To prevent the computational complexity for calculating the maximizing term (Eq. (28)), the robust linear optimization formulation was introduced as follows (Bertsimas and Sim, 2004):

$$\begin{aligned} &Maximize \quad Z = \boldsymbol{cx} \\ &Subject \quad to \quad \sum_{j=1}^{n} \bar{a}_{ij}x_{ij} + z_i\Gamma_i + \sum_{j=1}^{n} p_{ij} \leq b_i, \qquad \forall\, i \\ &\qquad z_i + p_{ij} \geq \varepsilon\bar{a}_{ij}f_j, \qquad \forall\, i, j \\ &\qquad -f_j \leq x_{ij} \leq f_j, \qquad \forall\, i, j \\ &\qquad x_{ij}, z_i, p_{ij} \geq 0, \qquad \forall\, i, j \end{aligned} \tag{29}$$

Where z, f, and p are non-negative additional variables. In optimal mode, f_j for all j is equal to $|x_{ij}|$. $\bar{a}_{ij}$ indicates the nominal value of the uncertain parameter and $\varepsilon > 0$ indicates the given uncertainty level. $\hat{a}_{ij}$ is obtained through multiplication of the nominal value of variable ($\bar{a}_{ij}$)

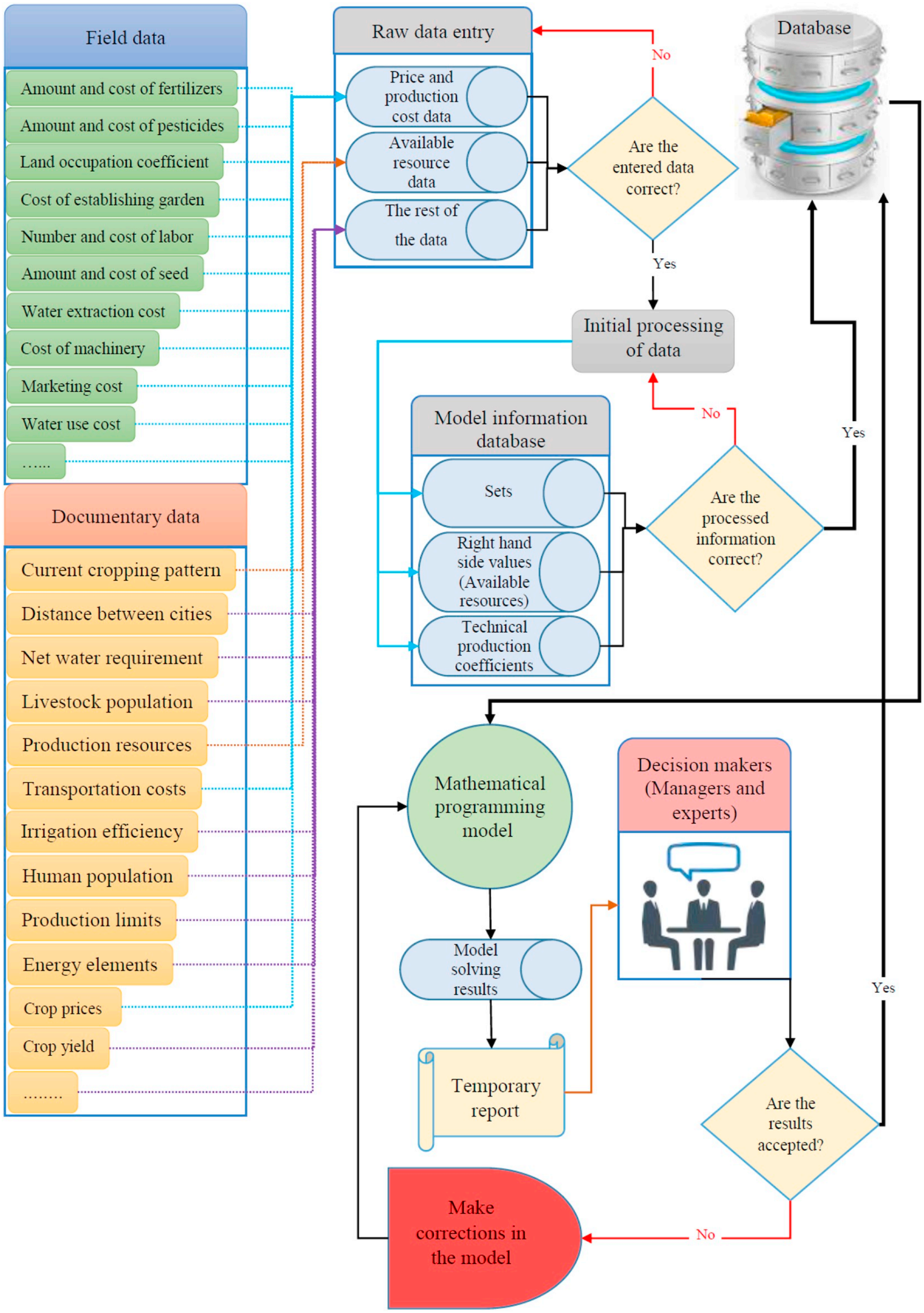

Fig. 2. A general overview of the communication between the three components of the cropping pattern development process.

by the given uncertainty level(ε). There are different values for Γ_i parameters. This depends on the probability of i^{th} constraint violation from its boundary (p) and also the number of uncertain parameters (n) within that constraint. By inserting x^* in Eq. (29) as the optimal answer, the probability of i^{th} constraint violation from its boundary is defined as:

$$pr\left(\sum_j \tilde{a}_{ij}{x^*}_j > b_i\right) \le B(n, \Gamma_i) \tag{30}$$

If the boundary n is determined by $B(n, \Gamma_i) \le (1-\mu)C(n, [\nu]) + \sum_{l=[\nu]+1} C(n, l)$, one can write:

$$C(n,l)=\begin{cases}\frac{1}{2^n}, & if\ l=0\ or\ l=n\\ \frac{1}{\sqrt{2\pi}}\sqrt{\frac{n}{(n-1)n}} & \\ \exp\left(n\log\left(\frac{n}{2(n-l)}\right)+l\log\left(\frac{n-l}{l}\right)\right), & otherwise\end{cases} \tag{31}$$

Where, $\mu=\nu[\nu]$, $\nu=(\Gamma_i+n)/2$and $n=|K_i|=|J_i|$.

To calculate Γ_i, an optimal level of the probability of constraint deviation i from the boundary of that constraint is considered, and given the number of uncertainty parameters (n) in that constraint, Eq. (29) is used to calculate it.

There are a lot of uncertain parameters in the model of regional cropping pattern. In this study, one of the most important uncertain parameters, that is, the amount of available water ($WaterRHS_m{}^{d2}$) has been taken into consideration. To prevent the addition of extra constraints to the model, and the computational complexity in solving the cropping pattern programming, other parameters available in the model were inferred with certainty.

To apply the uncertainty conditions in available water constraint (Eq. (4)), a general optimization form (Eq. (25)) is used. Thus, Eq. (4) is changed as follows in the model of regional cropping pattern, under uncertainty condition:

$$\sum_{j=1}^{J} Water\_V_{jm}^{d2}=\overline{WaterRHS}_m^{d2}+z_m^{d2}\Gamma_m^{d2}+p_m^{d2}\le 0 \qquad \forall\ d2,\ m \tag{32}$$

$$z_m^{d2}+p_m^{d2}\ge \varepsilon\,\overline{WaterRHS}_m^{d2} \qquad \forall\ d2,\ m \tag{33}$$

In order to evaluate the status of water resources in province, the Falkenmark Index was used to analyze the status of water resources balance after the implementation of the proposed model. In his studies, Falkenmark defined the water crisis based on the per capita annual renewable resources in each country, and introduced the water per capita of 1700 and 1000 cubic meters per year as an indicator of water stress and shortage, respectively (Falkenmark and Widstrand, 1992).

The last set of constraints was related to the decision variables being non-negative in the proposed model. Here, it should be mentioned that all variables listed in Table 1 should be non-negative (positive variables). However, the variables of the objective function on the left side of Eq. (1), including objectives 1–5, are exceptional (free variables).

2.3. Database and model links

Due to the large volume of input information (the parameters in Table 2 and the sets in Table 1), as well as the large number of equations (Eqs. (1) to (29)) and variables (Table 1), realization of objectives requires a widespread and sequential process for making decision on optimization of cropping pattern at the regional level (Fig. 2). In this process, there are three main components of the database, a programming model and, finally, a set of decision makers with an interconnected communication between their elements.

To better manage information, two database software including Microsoft SQL Server and Microsoft Access were used to speed up data analysis and facilitate access to data and prepare final reports, respectively. The mathematical algorithms of the programming model presented in the General Algebraic Modeling System (GAMS) software package were also coded. The programming model was directly and fully connected with the Microsoft Access database to receive processed data as well as load the results from the pattern resolution. In the meantime, the use of Microsoft Excel to connect the database of the model and the database itself was inevitable (this software was used to create a user interface for preparing reports as well as storing the raw data, temporarily). All primary (raw) data collected using documents and field studies were saved in the Microsoft Excel. The raw data was then transferred to the Microsoft Access for initial processing and the provision of the information required by the mathematical model. After creating query forms in Microsoft Access and related forms in Microsoft SQL Server, the data processing stage begins. The expert examines the processed data logically and, in the absence of any corrections, they are entered into the database.

3. The case study

The ability of the proposed model in this study was evaluated in Isfahan province, which includes 23 counties according to the last country divisions in 2013. Isfahan province is located in arid and semi-arid central area of Iran, which has always been influenced by drought phenomenon. The expansion of irrigated lands through the construction of irrigation networks and industrial development in Isfahan province consumes a considerable amount of water resources (Nikouei and Ward, 2013). Inappropriate spatial and temporal distribution of atmospheric precipitation and runoff shortage during the consumption seasons led to a situation where water needs of the province were mainly met through the excavation of aqueducts and deep and semi-deep wells (Shafiee and Safamehr, 2011). The calculation of relative water stress, which indicates the proportion of water consumption in the drinking, industrial, and agricultural sectors to the renewable water resources, shows that there is severe water stress in all of the counties and counties of the province (Nikouei et al., 2012).

The agricultural sector in Isfahan province is one of the most important economic sectors. According to agricultural statistics released by the Ministry of Agricultural Jihad in the year of 2013–2014, with 275,269 ha of total irrigated and dry lands, the Isfahan province accounts for 16.2% of the total land area of Iran, and in this regard, ranked 17th among the provinces of Iran. The study of annual production of agricultural products in Isfahan province during the studied year shows that Isfahan is ranked 7th in Iran. Having 14.3% of Iran's gardens, Isfahan Province has the 8th place among other provinces. Meanwhile, with production of about 394,000 tons of horticultural products, Isfahan Province accounts for 2.2% of the Iran's total production of horticultural products, and has 8th place among other provinces of Iran. The review of the above statistics indicates that the cropping pattern of the Isfahan province needs to be reviewed in terms of creating a codified and flexible program.

4. Results and discussion

Agricultural products in Isfahan province include 64 crops, which depending on the climatic and geographical conditions of each county, some of these crops are cultivated in different counties. Due to the large number of crops, eight main group of crops, including horticultural, pharmaceutical, and industrial crops, as well as cucurbits, vegetables, cereals and feed-stuff (forage) have been introduced. Throughout this study, these eight groups are used to provide better results. The highest frequency of product cultivation in the counties is related to wheat, barley, alfalfa, chickpea bean, potatoes and forage corn. The lowest abundance is related to the industrial and pharmaceutical products such as cumin, cannabis, tobacco, rhubarb and rapeseed, and the group of cereals and forages including grain and forage sorghum.

According to Table 2, a lot of data was needed for the province to implement the proposed model. The number of tables created in the database software is more than 800 tables. Also 130 query forms in Access and 80 view forms in the SQL were used to process the initial information and to report the final results. Data on the cost of production and prices of agricultural products were collected by completing 23 standard questionnaires of Ministry of Agricultural Jihad, separately for agricultural and horticultural products by the experts of each county in 2015. Of course, the information of the experts of this organization is about completing the same type of questionnaire for the number of different samples in each county. Other information was also obtained from sate organizations and administrations such as Ministry

of Agricultural Jihad, Agricultural and Natural Resources and Education Center, Mirab Zayandehrood Co. and Regional Water Organization of Isfahan Province.

The number of parameters after the initial processing of raw data in the GAMS software loaded for the study area included a total of one million data, which is summarized in Table 3 below.

Average production cost per unit area (hectare) for Isfahan province is 1156 and the average net profit is about 892 US $ per hectare. Three main groups of products, i.e. vegetables, cucurbits and horticultural products, incur higher production costs relative to other products, due to a higher use of labor and machinery during harvest, such that average production cost for these groups was 1660 US $ per hectares which was significantly different from the mean cost of all other products (30% higher cost).

The two groups of cucurbits and cereals have a negative net profit per hectare of cultivation of these agricultural products. In the main group of cereals, wheat is of special importance because of its strategic nature in providing food security to Iran. Therefore, despite the negative net profit of this crop, it is cultivated extensively (sometimes by the compulsion of state laws). In addition, in most counties that have a major contribution in cultivating wheat, the demand is high due to the rural texture of the region. These two factors together make the wheat crop, which contributes a 69% share of cereals in this province to be cultivated, and create a negative net profit for this crop. It should be noted that in the proposed model, all these limitations are considered.

The major reason of negative net profit of cucurbits is attributed to cucumber and tomatoes. The crop area of one or both of these products has increased in some years that resulted in a severe reduction in their price, such that it could not even cover the current costs of the crop area for these two crops. Considering that about 73% of the cucurbits crop area is attributed to cucumber and tomatoes, it is expected to have a negative net profit in this group.

The average water requirement is 6.79 thousand cubic meters per hectare. It should be noted that the irrigation efficiency in the county under study was very different, and according to Eq. (3), this was considered in the model. Average irrigation efficiency in Isfahan province was 37%.

Now the results of the comprehensive regional cropping pattern model, which is one of the subsets of the Multi-Objective Structural Planning (MOSP) approach is provided, and different objectives, such as economic, social and environmental objectives are discussed. Considering the importance of each objective, summed up by the experts of the Agricultural Jihad Organization of Isfahan province using the AHP method, weights considered to solve the multi-objective planning model for maximizing net profit and the use of labor, minimizing the cost of fertilizers, chemical pesticides, and net energy export, as well as maximizing net virtual water imports are 0.25, 0.1, 0.1, 0.1, 0.15, and 0.3, respectively.

To solve a multi-objective programming model, the payoff matrix should be formed. To this purpose, first, all objectives under study should be optimized separately. Then, using the optimal values from separate objective optimization, a multi-objective model is solved to establish reconciliation between single objectives. In other words, in the present study the proposed model is solved 7 times; 6 times to solve the single objectives and once for solving multi-objective programming. It should be noted that the third objective in Eq. (1) includes two separate minimizing objectives (minimizing the costs of fertilizers and chemical pesticides). Therefore, the optimal responses are reported as individual and multi-objectives.

The optimization method chosen to solve this model was CONOPT4, which is an optimizer for solving large-scale nonlinear programming problems. CONOPT4 works according to the Generalized Reduction Gradient (GRG) methodology and has been developed in GAMS by the ARKI Advisory and Development Company in Denmark (GAMS/CONOPT4, 2015). It should be noted that solving the proposed model for the study area resulted in the creation of 283 thousand equations and 558 thousand variables.

As mentioned earlier, various climatic conditions create some errors in estimating important parameters of optimal cropping pattern, including the amount of water available. Therefore, when modeling the cropping pattern, robust optimization was used to reinforce the model against data volatility in the proposed model. Considering the severe fluctuations in precipitation in Isfahan province, parameter Γ using which the conservation could be controlled, was calculated at the probability of $p = .01$ using Eq. (31), and the result, i.e. 0.7, was replaced in Eq. (32). Therefore, the proposed model is protected against the changing climate, which mostly affects precipitation and thus the available water.

Table 4 presents the cropping pattern report of Isfahan province crops, separately for each objective (6 single objective and 1 multi-objective) and crop group. It is observed that the total crop area of all models (except for the maximization model of labor force utilization and net energy import minimization) has decreased, so that the total crop area has been reduced from 332,809 ha in the current pattern to 278,010 ha in the multi-objective model (16% decrease).The important point in interpreting this table is the fact that the multi-objective proposed model in all product groups represents a reduction in the crop area and only represents a 10% increase in the horticultural product group. Good soil conditions as well as high net profit for pistachio, almond, and apple in some counties have led to the recommendations to increase the crop area of horticultural products.

Unlike other models, the proposed crop area in the minimizing net energy imports model, shows an increasing trend due to the high energy consumption from the two groups of cereals and forage crop, in contrast to other models (an increase of 3% for the forage crop group and an increase of 11% for the crop group grains).

Increased crop area in t the minimizing net energy imports model has prevented a more severe reduction of the crop area in the MOP model. Therefore, the transportation issues have had a significant effect on the cropping pattern. Considering the fact that the main crop areas in Isfahan province are located in water prohibited plains, due to the excessive withdrawal of water from underground aquifers (Shafiee and Safamehr, 2011), it is not unlikely to accept these results within the framework of a structural planning.

Various studies carried out in the province over the last few years also indicate that the balance of water resources for agricultural purposes cannot be achieved through the development of water saving systems alone (Nikouei and Ward, 2013; Nikouei et al., 2012; Sabouhi and Mardani, 2013).

Due to the increase in the crop area in the group of horticultural, for a multi-objective model, compared with the current crop area, Fig. 3 shows the changes in the crops of this group. It is seen that in this

Table 3
The value of some important elements for the eight main groups of crops in the Isfahan province.

Elements	Cereals	Forage	Cucurbits	Industrial	Vegetables	Pharmaceutical	Grains	Horticultural	Average
Total Cost (US $/ha)	937	1173	1681	784	1685	353	1021	1612	1156
Net benefit (US $/ha)	−47	857	−295	1275	968	481	27	3868	892
Production (ton/ha)	4.37	38.04	27.74	6.13	24.61	0.8	1.62	5.73	13.63
Net water (1000m^3/ha)	5.31	10	6	6.72	6.37	5.84	5.59	8.52	6.79
Calories (Kilos calories/ha)	11,149	58,503	16,119	4226	11,115	20	2350	4739	13,528

Table 4
Cropping pattern of crops in Isfahan province, in terms of the single and multi-objective optimization and the main group of crops (Unite: hectare).

	Single Objective							Multi-objective	
Main group of crops	Current cropping pattern	Maximizing net profit	Maximizing net virtual water imports	Minimizing net energy imports	Maximizing the use of labor	Minimizing pests control costs	Minimizing fertilizers costs	Multi-objective	Multi-objective variations percentage
Horticultural	77,560	110,786	80,907	83,692	78,938	80,434	83,201	85,222	9.88
Grains	10,962	1414	1096	1320	20,415	1972	1690	1097	−89.99
Pharmaceutical	1930	1112	362	362	3626	3684	2943	362	−81.24
Vegetables	23,378	25,625	15,556	34,361	42,782	21,058	20,296	20,526	−12.20
Industrial	7248	4625	1877	1179	5393	6391	4340	4669	−35.58
Cucurbits	8098	9784	2970	10,404	16,705	4778	4364	5576	−31.14
Forage	48,861	38,646	41,923	50,365	33,000	49,027	46,298	46,231	−5.38
Cereals	154,772	131,669	113,347	172,578	144,864	99,020	94,239	114,327	−26.13
Sum	332,809	323,661	258,038	354,261	345,723	266,364	257,371	278,010	−16.46

model, apple has the largest crop area among the horticultural products. This is while the largest area in the multi-objective model is associated with pistachio, so that the area of this product has increased from 7451 ha in the current model to 11,655 ha in the multi-objective model (56% increase in the crop area). The high export capacounty of this crop resulted from the high profitability and the cultivation constraints because of different quality water requirements that are not available in other areas (Arabnezhad et al., 2011), has led to a reasonable increase in the cultivation area.

The amount of import and export of crops is divided into two parts inside and outside the province. As far as the intra-provincial exchanges are concerned, all the origins and destinations are within the province; in other words, the counties located in Isfahan province are considered as supply and demand centers for the crops. In trans-provincial exchanges, each county is individually linked to a destination outside the province. The assumption considered for the trans-provincial exchanges is that a certain province has not been considered for trading with Isfahan province, and the cost of transportation has been calculated using the average distance traveled outside the province. Due to the lack of information about inter-county exchanges, the volume of export and import within the province cannot be calculated and only trans-provincial exchanges have current values.

By calculating the energy equivalent for each crop, the net amount of energy imports can be easily calculated for each county. All exchanges of crops and net imports of energy are shown in Table 5. It is noticeable that the Isfahan county has the highest rate of intra-provincial imports in all studied models, due to the considerable demand for crops. The domestic export of 71 thousand tons made Falavarjan county to be ranked first in terms of this parameter in the MOP model. The important point in examining intra-provincial exchanges is the numerical equalization of the total intra-provincial volume of exports and imports that has been made according to the conditions created in the proposed model. In the MOP model, the highest volume of exports to the outside of province is associated with Isfahan county with an amount of 698 thousand tons, and the smallest amount is associated with Chadgan county, with an amount of 3000 tons (96% decrease compared to the current model). An increase of 132% in exports of crops from Shahinshahr-va-Meymeh county to the outside of the province has put this county at the center of attention for the increase of the export of proposed crops. It is observed that total exports to the

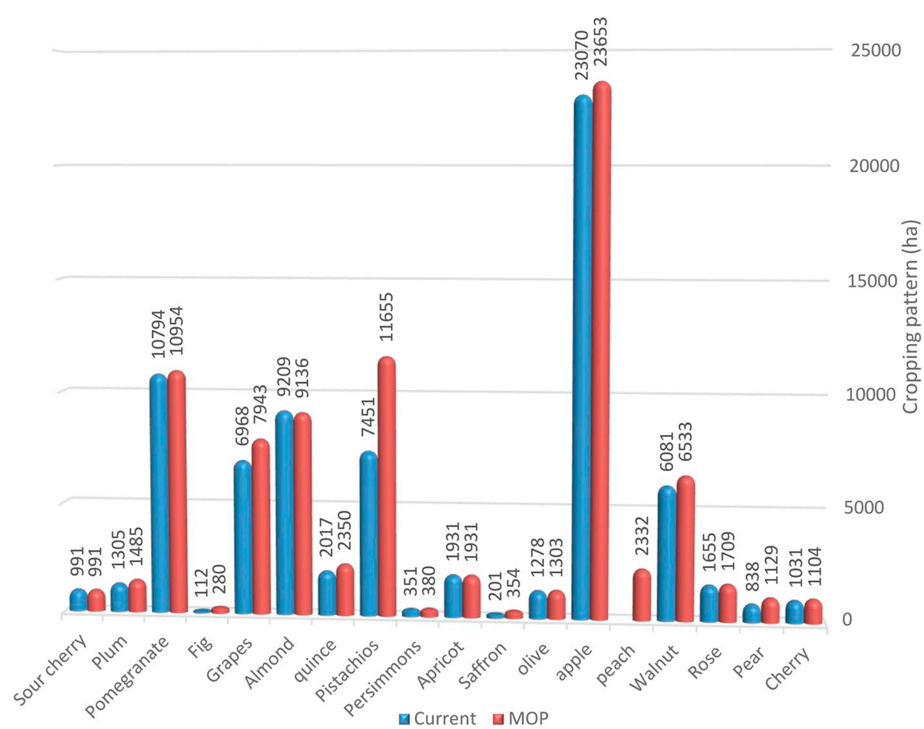

Fig. 3. Optimal crop area of the horticultural group for the MOP model.

Table 5
Intra-provincial and trans-provincial exchanges of crops and net energy imports in Isfahan province, separately for each county in the MOP model.

County	Net import energy (Million calories)			Import from outside the province (Thousand tons)			Exports to the outside of province (Thousand tons)			Intra-provincial imports (Thousand tons)	Intra-provincial exports (Thousand tons)
	MOP variations percentage	MOP	Current	MOP variations percentage	MOP	Current	MOP variations percentage	MOP	Current	MOP	MOP
Aran-va-bidgol	15	−88	−104	−69	9	29	−11	74	83	2.9	5.48
Ardestan	9	−129	−141	−28	13	18	−14	79	92	2.1	0
Isfahan	9	418	384	−84	110	673	77	698	394	91.3	17.64
Tiran-va-karvan	14	−178	−206	−8	36	39	60	297	186	1.2	0
Chadegan	4	−47	−49	−47	10	19	59	70	44	2.2	0
Khomeinishar	−23	−171	−139	−18	9	11	−96	3	71	28.9	50.47
Khansar	10	143	130	−31	71	103	76	30	17	18.3	0
Khor-va-biabanak	9	−20	−22	−14	6	7	67	5	3	0	0.85
Dehaghan	86	−1	−7	−33	6	9	−65	12	34	5.9	0
Semirom	7	−56	−60	−85	12	81	−19	298	370	3.6	16.41
Shahinshar-va-meimeh	8	−215	−234	15	55	48	132	248	107	27.2	37.92
Shahreza	21	−100	−127	−33	29	43	37	160	117	10.7	0
Feridan	12	−125	−142	4	25	24	7	111	104	5.7	8.6
Feridonshahr	11	−153	−171	−80	8	41	5	62	59	0	21.25
Falavarjan	−20	−79	−66	−16	48	57	−43	66	116	15.8	6.68
Golpayegan	900	10	1	31	17	13	−66	43	125	1.8	70.65
Lenjan	8	−143	−155	−31	67	97	0	9	9	6.6	33.18
Mobarakeh	12	86	77	−55	19	42	63	155	95	11.9	0
Naein	15	−70	−82	−52	11	23	100	4	2	2.1	6.12
Najafabad	500	12	2	−60	39	98	61	45	28	0.1	0
Natanz	8	121	112	−33	8	12	4	79	76	20.3	3.71
Kashan	12	−69	−78	−64	46	129	76	95	54	4.8	0
Aran-va-bidgol	72	124	72	–	110	673	–	698	394	15.6	0
Maximum	–	418	384	–	6	7	–	3	2	91.3	70.65
Minimum	–	−215	−234	−59	663	1631	21	2653	2195	0	0
Sum	27	−730	−1005	−69	9	29	−11	74	83	279	279

outside of the province increased from 2195 thousand tons in the current model to 2653 thousand tons in a MOP model, which resulted in an increase of 21% in the export rate.

Of 23 counties in the Isfahan province, Khomeini Shahr, Falavarjan, Lenjan, Najafabad and Kashan have imported energy in all the models (a positive indication for the import), while the other counties had energy exports (a negative indication for export). A survey of net energy imports in Isfahan province indicates a negative balance of energy imports. Nevertheless, net energy imports in the MOP model have been reduced; so that the net amount of energy exported reduced from the 1005 million calories in the current model to 730 million calories in the MOP model (a decrease of 27%). This reduction has occurred when the export rate increased. This is due to reduced exports and increased imports of high-calorie crops (such as cereals).

Table 6 reports some important economic variables such as gross profit and cultivation cost of crops, import costs, net profit of the export of crops and net profit in the Isfahan province. It is seen that the net profit in the current situation is lower than all models. For example, the total net profit in the MOP model is 482 million US$, which has increased by 58% compared to the current model. Increasing profits in conditions of optimal cropping pattern has been carried out for some areas of Isfahan province in a number of studies (Nikouei and Ward, 2013; Nikouei et al., 2012; Sabouhi and Mardani, 2013). Nevertheless, in none of these studies there was a regional perspective for the whole province with the exchange of products.

The net export profit was less than the current conditions in all studied models, such that the difference between the net export profit in the multi-objective model and the current model was 81 million US $ per year (a reduction by 476%). Considering that Isfahan is facing severe water crisis, and in the proposed model the priority is given to maximizing virtual water import (the highest weight for this objective), this result seems reasonable for the current conditions.

As Falcon Mark's renewable water per capita index shows (Table 7), the counties of Isfahan, Khomeinishahr, Falavarjan, Kashan, Lenjan, Mobarakeh and Najafabad are facing a shortage of water and a water crisis. Despite the large population of these counties (about 77% of the province's population), the renewable resources of these seven counties make up only about 18% of the total renewable water resources of the entire province. It is also clear that the counties of Aran-va-Bidgol, Borkhar, Shahinshahr-va-Meymeh and Shahreza have water stress.

The survey shows that among the mentioned counties, only Najafabad and Khomeinishahr have net imports of virtual water with values of 1 and 1.7 million cubic meters (A positive sign of import), and the other counties have net exports of virtual water (A negative sign of export). For example, in the current situation in Isfahan, 21.7 million cubic meters of net exports of virtual water was due to transportation of crops, which is ranked first among the other counties. In this situation, the county of Semirom, with 19.4 million cubic meters, is ranked second in terms of the export of virtual water, which is an indication for not having any water stress. The bottom row of Table 7 shows that in the current situation, the net import rate of virtual water is much less than the net export rate. This caused the province of Isfahan to have 11.78 million cubic meters of net virtual water exports.

The largest amount of virtual water transportation in the MOP model is related to the total trans-provincial imports of 67.7 million cubic meters and total intra-provincial exports of 49.9 million cubic meters. The net import of virtual water was improved in the MOP model, compared to the current situation, through the difference of the net import of virtual water under current condition and under the MOP model, which represents an improvement in the status of virtual water imports in all counties other than Khore-va-biyabana. For example, in the county of Kashan, the improvement in net virtual water imports in the MOP model is 11.1 million cubic meters. In total, with the implementation of MOP model, 17.8 million cubic meters of net virtual

Table 6
Some important economic variables, in terms of the single and multi-objective optimization in the Isfahan province (Unit: Million US $).

	Single Objective							
Variables	Current cropping pattern	Maximizing net profit	Maximizing net virtual water imports	Minimizing net energy imports	Maximizing the use of labor	Minimizing pests control costs	Minimizing fertilizers costs	Multi-objective
Gross profit	669	901	594	702	713	615	618	706
Cultivation cost	313	333	227	304	306	231	233	261
Import costs	47	72	48	56	54	49	47	54
Net profit of export	98	8	20	18	19	18	18	17
Net profit	304	633	395	437	443	415	415	482

water imports are estimated for the Isfahan province, which improves the net import of water by 136.5 million cubic meters. This is exactly the amount of virtual water that can be saved through the implementation of regional cropping pattern. This result shows that the production of crops in the counties located in Isfahan province is very inefficient in terms of virtual water transfer; so that most of the exports are related to the products that require a lot of water.

It is seen that in all counties, the renewable water resource per capita index (Falcone Mark) has been improved and shows a positive number. In general, the average improvement in the Falcon Mark's renewable water resource index is estimated to be about 119 cubic meters per year.

Another important issue in programming for agricultural products is the sustainability and optimal use of production factors of agricultural products. This was clearly included in the objectives of the present study (Eq. (1)). Table 8 provides useful information on the optimal use of production factors in the current and the multi-objective cropping pattern, and the way they influence sustainability of agricultural products in Isfahan province.

Reduction in the irrigation water consumption, fertilizers and chemical pesticides which are considered as the ecologic objectives in the sustainability of agricultural products, was well conducted in the proposed multi-objective model, such that the amount of irrigation water consumption will be reduced by 20% in case of changing the current cropping pattern. Fertilizers and chemical pesticides, which are considered as inputs disturbing the sustainability in production, will be reduced by 14 and 12%.

The number of labor increases by 9%, which will lead to job creation in the agriculture sector in Isfahan. It should be noted that labor input should be considered from another aspect, i.e. reducing the production costs. Therefore, objective 4 (Eq. (1)) should be changed into minimizing labor use. With regard to the excessive unemployment in the rural areas of Isfahan, job creation is an important social objective in the region. Therefore, in the present study, a special attention was paid to maximizing labor use, and it was realized in the optimal pattern of multi-objective model. A 37% increase in the total gross profit confirms the economic aspect of sustainable production in the proposed model.

Providing food security is an important objective in every country. Supplying the energy demand of the people to perform their essential life activities is directly related to food security. The energy produced by consuming agricultural products could be a good criteria to investigate the case.

Table 9 shows the energy produced in various models of cropping pattern separately for the main groups of products. In the minimizing pattern of net energy import, the highest energy production rate was related to cereals by 3062 million calories, and this also stands for the multi-objective pattern by 1984 million calories. Obviously, it should be noted that changes in energy production in the minimizing pattern of net energy import were positive (a 21% increase) and, they were negative in the multi-objective pattern (a 22% reduction). This was due to the reduced crop area of wheat with a relatively high food energy in this group. In the products set, the amount of produced energy was 4837 million calories, which increased to 6839 million calories in the minimizing pattern of net energy import (a 43% increase), and 4922 million calories in the multi-objective pattern (a 2% increase).

It is worth mentioning that increased energy production from consuming the cultivated agricultural products more than the demand in the society, which is among important issues in food security, could not be regarded as a positive point for a pattern. Therefore, considering that in all models, minimum energy demand was considered, excessive energy production would waste the resources.

As stated in the conceptual framework of cropping pattern (Fig. 1), one of the important components of optimal cropping pattern is the country's macro policies. Major rules related to the cropping pattern in Iran are related to 4 Articles each of which emphasizes part of this case. A summary of the assessment of the proposed multi-objective model in this study is reported in Table 10 on considering the country's macro policies. As could be seen, all issues in Article 13 on determining the duties of agricultural organizations affiliated with the Ministry of Agriculture emphasize planning to develop a suitable cropping pattern based on the region's potentials. According to what provided in the table, the proposed model is capable of applying all three sections of this Article, which are related to the cropping pattern, according to the structure created in it. On the first part of this law which deals with determining the most suitable products, it could be said that the major available variable in this study ($Land\_V_j^{d2}$) the optimal responses of which are shown in Table 4, clearly responds to the programming managers' demands. Obviously, it should be noted that this variable is determined in a range where the basic demands of the country are supplied, and it is mostly upon Eqs. (8) and (9).

Article 17 of the act on determining the duties of agricultural organizations affiliated with the Ministry of Agriculture mostly emphasizes the sustainability issues of agricultural product resources, especially the irrigation water. This was noted in objectives 2 and 3 (Eq. (1)) which assist minimizing the consumption of ecosystem disturbing inputs and water consumption respectively. It should be noted that Eqs. (3) and (4), which deal with determining the extent of using water resources, also affect the achievement of this objective, such that by creating the allowable exploitation limit from the plains of the area under study that are exposed to water shortage, some problems related to unprogrammed exploitation of water resources could be solved.

In Article 6 of the Act on the promotion of efficiency in the agriculture sector, economic issues are of high importance. Objective 1 in this study (Eq. (1)) is considered due to the importance of economic issues. However, it should be noted that with regard to the transportability of the products in the proposed model, and its relation with the first objective, it could be said that production is fairly observed considering the relative advantage of the products. By a few changes in the proposed model, and providing a database for all provinces of Iran, the transportability of products could be comprehensively employed, and by increasing the scope of the study, the relative advantage could be

Table 7
Virtual water transfer rate in the province of Esfahan in the form of intra-provincial and trans-provincial per county (Unit: thousand cubic meters).

Counties	Current amount of Renewable water per capita index (cubic meter per year)	Falcon Mark's Index	Total imports from outside the province (MOP)	Total exports from outside the province (MOP)	Total intra-provincial import (MOP)	Total intra-provincial export (MOP)	Virtual water net import (Current)	Virtual water net import (MOP)	Improvement of net virtual water import	Improvement of renewable water per capita indicator (Cubic meter per year)
Aran-va-bidgol	1062	Adventure of stress	1711	2708	0	126	−7586	−1123	6463	52
Ardestan	4355	No Stress	3949	5229	352	0	−7544	−928	6616	80
Isfahan	283	High sterss	4330	460	0	26	−21,699	3844	25,543	38
Tiran-va-karvan	1544	Adventure of stress	5140	252	0	615	−3167	4273	7440	46
Chadegan	3749	No Stress	2222	2936	0	71	−5316	−785	4531	41
Khomeinishar	10,616	No Stress	124	1561	0	190	−4821	−1627	3194	92
Khansar	87	High sterss	5491	1747	1037	0	1029	4781	3752	193
Khor-va-biabanak	2981	No Stress	464	1284	0	2	−2206	−822	1384	2
Dehaghan	5200	No Stress	57	818	0	29	−538	−790	−252	33
Semirom	2776	No Stress	1871	747	0	912	−2340	212	2552	80
Shahinshar-va-meimeh	25,580	No Stress	1545	13,065	391	0	−19,651	−11,129	8522	35
Shahreza	1211	Adventure of stress	400	214	0	392	−3408	−206	3202	85
Feridan	1032	Adventure of stress	478	2580	103	274	−5443	−2273	3170	252
Feridonshahr	4792	No Stress	222	2539	0	462	−6513	−2779	3734	131
Falavarjan	49,530	No Stress	10,558	1372	0	399	2143	8787	6644	414
Golpayegan	306	High sterss	3149	583	1339	0	−3411	3905	7316	121
Lenjan	1897	No Stress	325	173	0	2022	−19,291	−1870	17,421	242
Mobarakeh	457	High sterss	2607	1270	1577	1177	−371	1737	2108	44
Naein	790	High sterss	2692	2500	0	98	−5127	94	5221	52
Najafabad	2490	No Stress	2811	0	53	5	677	2859	2182	11
Natanz	754	High sterss	7032	3098	328	0	1752	4262	2510	194
Kashan	2789	No Stress	79	2265	0	124	−4483	−2310	2173	232
Aran-va-bidgol	403	High sterss	10,484	2545	1744	0	−1415	9683	11,098	278
Sum	–	–	67,741	49,946	6924	6924	−118,729	17,795	136,524	–

Table 8
Main parameters related to sustainability in production and optimal use of production factors of agricultural products in Isfahan.

	Net profit (Million US $)	Number of labor (Thousand Man-day work)	Amount of pesticides (Thousand liters)	Amount of fertilizer (Thousand tons)	Amount of irrigation water (Million cubic meter)
Current cropping pattern	304	4214	19	243	4580
Multi-objective	482	4650	17	213	3870
Multi-objective variations percentage	37	9	−12	−14	−20

investigated more accurately.

Cropping pattern determination based on climatic conditions (Article 26 of the Act) in this model is possible only through production constraints (Eqs. (4) and (8)) or the crop area (Eq. (2)) which provided acceptable results in the regional scale (inter-county). The details of cropping pattern determination based on climatic conditions should be specified in the operational planning through conducting accurate pedological, hydrological and climatological field studies. Therefore, in the structural planning, this Act could relatively address the needs.

5. Conclusion

The amount of agricultural products cultivation in a given region should be done according to available resources, crop prices, production costs, product performance, country needs and macro policies. Deciding whether or not to plant agricultural products in different regions should be based on the existing infrastructure, as well as social, economic, environmental and technological issues, by maintaining the basic production resources to meet the basic needs of the country. In the proposed structure of this study, there are eight main aspects of defining the cropping pattern: planning, production stability, optimal utilization of production resources, transportation of crops, food security, macro policies of the country, climate conditions, and environmental considerations for 23 county located in Isfahan province.

From programming perspective, in the present study, the comprehensive regional cropping pattern for agricultural products was designed which was a subset of the multi-objective structural planning (MOSP). In this model, various objectives and constraints were employed that resulted in the achievement of the objectives. Considering fluctuations in climatic conditions, preserving this model against changes in the estimated data was considered. To apply the uncertainty conditions resulted from climatic changes, robust optimization method was used.

A significant reduction in irrigation water consumption by 20%, improved renewable water per capita (Falcon Mark index) by 119 cubic meter per year, and a reduction in virtual water import by 5.136 million cubic meter per year will assist the achievement of production sustainability objectives (ecologically) and optimal use of agricultural production resources. In addition, increased total gross profit by 178 million dollars per year, and the use of more labor were other achievements of the proposed model that result in reinforcement of the socio-economic dimension for sustainable production.

Reduction of using environment-disturbing inputs (fertilizers and chemical pesticides) was in line with the objectives of the study in terms of both environmental considerations and use of production resources. In the proposed multi-objective pattern, the use of fertilizers and chemical pesticides reduced by 14 and 12% respectively.

Energy production by consuming cultivated products increased by 2%. Despite that this change appears insignificant, a 27% reduction in net energy import was observed which appears effective in achieving food security.

Among various acts related to cropping pattern, four articles are of special importance, and, it was specified that the proposed model could respond to a major part of these acts, and it is in line with the country's macro policies.

Considering the results of this study, some recommendations are provided in higher (strategic) and lower (operational) levels of the structural planning as follows:

1. Results from investigating cropping pattern in the multi-objective model relative to the current crop area suggested the reduction in crop area of agricultural products in Isfahan (by 16.5%) Therefore, in the future, the crop area of the agricultural products should be reduced and instead, by changes in the provincial cropping pattern, the strategies should be changed toward increased exploitation of water resources. From a planning perspective, the strategic planners should be announced to create encouraging and preventive rules to reduce the crop area, and the operational planners should be informed to promote and administer these rules.
2. Irrigation water consumption reduced by changing the current cropping pattern, and, it will contribute to the sustainability of agricultural products. Adopting policies to achieve this goal, including available water reduction policies (like installing smart water meter and excluding the unlicensed wells) are recommended. In this regard, strategic planners are responsible to provide and draft rules and guidelines for these policies to create good infrastructures,

Table 9
The amount of energy produced by the cultivated agricultural products in Isfahan separately for the product and objectives under study (in million calories).

	Single Objective							Multi-objective	
Main group of crops	Current cropping pattern	Maximizing net profit	Maximizing net virtual water imports	Minimizing net energy imports	Maximizing the use of labor	Minimizing pests control costs	Minimizing fertilizers costs	Multi-objective	Multi-objective variations percentage
Horticultural	524	765	531	585	532	543	588	592	13
Grains	16	3	1	2	29	6	4	1	−95
Pharmaceutical	0.34	0.2	0.06	0.06	0.64	0.64	0.52	0.06	−82
Vegetables	505	609	370	821	973	495	490	496	−2
Industrial	43	28	7	6	28	50	32	34	−22
Cucurbits	88	108	56	146	159	74	58	75	−15
Forage	1122	1165	1875	2217	988	1955	1983	1741	55
Cereals	2539	2293	1995	3062	2442	1729	1684	1984	−22
Sum	4837	4971	4835	6840	5153	4853	4840	4923	2

Table 10
Investigating the ability of the introduced multi-objective structural model in applying the country's macro policies on cropping pattern.

Capability Assessment	Details of the act on cropping pattern	Article of the Act
✓	• Determining the most appropriate products and recommendable activities in each region	Article 13 of the Act on determining the duties of the organizations affiliated with the Ministry of Agriculture
✓	• Arrangement and proposing the annual cropping program based on the country's demands for basic agricultural products	
✓	• Natural resources and ecosystem preservation while maximizing the production of agricultural products and minimizing water consumption	Article 17 of the Act on determining the duties of the organizations affiliated with the Ministry of Agriculture
!	• Determining the cropping pattern of each region based on relative advantages	Article 6 of the Act on promotion of efficiency in the agriculture sector
✓	• Determining the regional cropping pattern based on value added and economic conditions.	
!	• Determining the regional cropping pattern based on climatic conditions	Article 26 of the Act on promotion of efficiency in the agriculture sector

and, operational planners are responsible to implement them.

3. Isfahan province is regarded as one of the country's industrial poles. According to the results, the potentials of Isfahan province to increase employment is restricted. The strategic planners are strongly recommended to provide more industrial growth in this sector to transfer the surplus labor of agriculture sector to the industry sector. In addition, the operational planners should be careful in promoting agricultural machineries and maximizing mechanization, and, they should prevent disemployment by precise surveys.
4. Falcon Mark's index of measuring renewable water per capita in the current situation indicated the critical condition of water resources in some counties of Isfahan, including the most populous counties of Isfahan, Najaf Abad and Kashan, and, using encouraging or preventive policies to prevent cultivation or exportation of the products with high water demand such as rice and watermelon in these counties will be a great help to reduce net virtual water export. Among preventive measures are to prohibit the cultivation of the products mentioned along with prosecution by the operational planners and its powerful implementation by executive planners.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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